



**Fermilab**

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ALTERNATIVE SCHEMES FOR HIGHER  
 $\bar{P}$ -PRODUCTION AT FERMILAB

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It has been proven that luminosity of  $10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$  for  $p\bar{p}$ -colliding beam experiments can be achieved with over  $10^{11}$  anti-protons.<sup>7</sup> The problem remains of the fast collection of such large quantity of particles. Two schemes have recently been proposed, one in CERN and another at Fermilab, the former using stochastic cooling at large energies and the latter electron cooling at low energies. The steps involved in these two schemes are summarized in Tables I and II respectively.

The crucial parameter is the accumulation rate of antiprotons. It seems that the CERN scheme has a rate seven times larger than that of the Fermilab scheme. It is relevant then to check whether the modification of the Fermilab scheme to include stochastic cooling could yield to larger  $\bar{p}$ -accumulation rate. At the same time we want to stress the advantages of some beam manipulation techniques before targeting, like, for instance, RF stacking in the Energy Doubler or rebunching in the Main Ring at 80 GeV.

We list in the following few alternatives for Fermilab.

Table I. The CERN Scheme

1. Fill the CPS with  $N \sim 10^{13}$  protons in five bunches over a length which matches the cooling ring circumference.
2. Accelerate to 26 GeV/c. CPS acceleration cycle = 2.6 sec.
3. Extract and target to produce  $\bar{p}$  at 3.5 GeV. Transfer to the cooling ring. The yield assumed is  $2.5 \times 10^{-6} \bar{p}/p$  over a horizontal and vertical acceptance of  $100\pi \cdot 10^{-6} \text{ m}$  each and a momentum bite of 1.5%. Total number of  $\bar{p}$  injected in the cooling ring =  $2.5 \times 10^7$  per pulse.
4. Stochastic cooling (momentum-wise) of the fresh pulse. Cooling time  $\approx 2$  sec. RF stacking of the pulse for storage.

5. Steps 1 to 4 are repeated in sequence several times until  $6 \times 10^{11}$   $\bar{p}$  have been collected and stored.

Accumulation Rate =  $10^7$   $\bar{p}$ /sec

Filling Time = 24 hours, including a safety factor of 40%

Table II. The Fermilab Scheme

1. Fill the Main Ring with  $N \sim 2 \times 10^{13}$  protons with 13 Booster batches in  $\sim 1000$  bunches. Filling time 0.8 sec.
2. Accelerate to 80 GeV in 0.8 sec. Flat-top.
3. Extract a Booster length beam segment and target to make  $\bar{p}$  at 6 GeV. The yield assumed is  $2 \times 10^{-7}$   $\bar{p}/p$  over a horizontal and vertical acceptance of  $4\pi \cdot 10^{-6}$  m each and a momentum bite of 0.3%.
4. Decelerate  $\bar{p}$  in the Booster and transfer to the cooling ring.
5. RF stacking and simultaneously electron cooling. Cooling time  $\sim 50$  msec, less than Booster repetition period (67 msec).
6. Repeat steps 3, 4 and 5 thirteen times until all protons have been targeted and the Main Ring is empty.
7. Lower Main Ring field down to injection value in 0.4 sec. The entire sequence takes 2.8 sec and  $4 \times 10^6$   $\bar{p}$  are produced per cycle.
8. Repeat steps 1 to 7 several times until  $10^{11}$   $\bar{p}$  have been collected and stored.

Accumulation Rate =  $1.4 \times 10^6$   $\bar{p}$ /sec

Filling Time = 24 hours, including a safety factor of 15%.

Alternative I

Replace electron cooling with stochastic cooling in the original scheme shown in Table II. Extrapolation from CERN data

and assuming that the device is basically a replica of the one proposed for the CERN scheme<sup>1</sup>, namely same electronic gain and number of pick-ups, gives a cooling time comparable to the Booster repetition period<sup>2</sup>. Though this is a good alternative in the case the electron cooling is proven not working or too slow, nevertheless it does not ameliorate the production rate of antiprotons.

### Alternative II

Stochastic cooling at 6 GeV. This requires the construction of a new ring (storage ring) about the same size of the Booster as it has been proposed several times.

Stochastic cooling is characterized by larger phase space acceptance but longer cooling time than electron cooling. Besides there is also a mismatch between the natural  $\bar{p}$  production cycle time and the cooling (or precooling) time using stochastic cooling.

To realize stochastic cooling and accumulation at Fermilab, one could use a combination of the same production cycle as for electron cooling and the storage sequence as proposed in the CERN scheme.

After steps 1 and 2 shown in Table II the following steps are now:

3. Extract a storage ring-length beam segment and target to make  $\bar{p}$  at 6 GeV. We take the same yield assumed in the CERN scheme:  $2.5 \times 10^{-6}$   $\bar{p}/p$  over a horizontal and vertical emittance of  $100\pi \cdot 10^{-6} \text{ m}^2$  each and a momentum bite of 1.5%.
4. Transfer to the storage ring, pre-cool the fresh pulse within 2 seconds (momentum wise) and RF stack. We are adopting the same cooling time proposed in the CERN scheme.
5. Repeat steps 3 and 4 thirteen times until all protons have been targeted and the Main Ring is empty. The Main Ring flat-top is then  $13 \times 2 = 26$  sec long.

6. Lower Main Ring field down to injection value in 0.4 sec. The Main Ring cycle is 28 sec long and  $5 \times 10^7$   $\bar{p}$  are produced per cycle.

7. Repeat steps 1 to 6 several times until  $10^{11}$   $\bar{p}$  have been stored.

The accumulation rate is now  $1.8 \times 10^6$   $\bar{p}$ /sec, an improvement of 25%, but to somebody may be not enough.

### Alternative III

A considerable improvement could be obtained by eliminating the precooling and proceeding straight to the momentum stacking of the thirteen pulses from the Main Ring, followed by a two-second cooling period. Steps 4 and 5 in alternative II would now be replaced by:

4. Transfer to the storage ring and RF stack in 77 msec, which seems a reasonable time.

5. Repeat steps 3 and 4 thirteen times until all protons have been targeted and the Main Ring is empty. The Main Ring flat-top is now one sec long.

Steps 6 and 7 as in alternative II would follow but at the same time stochastic cooling (momentum-wise) would be applied to the stack of  $\bar{p}$  in the storage ring. As a matter of fact momentum cooling could be continuously applied also during stacking provided the pickups and the wideband cavities are placed at zero dispersion lattice locations where the freshly injected pulses are combined to the stack.

The Main Ring cycle is now 3 sec long which gives an accumulation rate of  $1.7 \times 10^7$   $\bar{p}$ /sec which represents an improvement of more than an order of magnitude. A total of  $10^{11}$   $\bar{p}$  could be collected in less

than two hours.

The idea behind this scheme is that the cooling time is not too sensitive to the  $\bar{p}$ -beam current if this is not too large<sup>2</sup>. Also computer simulations<sup>3</sup> have shown that indeed it is possible to cool a "hotter" fresh pulse on top of a "cold" stack, the signal being essentially given by the "hotter" beam. We understand that this is controversial and why indeed was not included in the CERN scheme, but we believe it deserves more consideration.

#### Alternative IV

One could use the Energy Doubler ring to momentum stack protons at 80 GeV from the Main Ring prior to extraction and targetry.<sup>5</sup>

After steps 1 and 2 shown in Table II the sequence would now be:

3. One turn extraction from Main Ring at 80 GeV. Transfer to the Energy Doubler. RF stacking<sup>4</sup>.
4. Lower Main Ring field to the injection value in 0.4 sec.
5. Repeat steps 1 to 5 ten times until  $2 \times 10^{14}$  protons have been collected. RF capture the beam at any desired frequency. At this stage steps 3, 4 and 5 of alternative II (which become steps 6, 7 and 8 respectively) are executed. The entire cycle is repeated until  $10^{11}$   $\bar{p}$  are accumulated.

The Main Ring/Energy Doubler cycle is now

$$10 \times (0.8 + 0.8 + 0.4) + 13 \times 2 = 46 \text{ sec}$$

which gives an accumulation rate of  $1.1 \times 10^7$   $\bar{p}$ /sec about what is proposed in the CERN scheme.

One crucial aspect of this scheme is clearly a 10-turn stack capability in the Energy Doubler. Also, the  $\bar{p}$ -production

target must survive the impact of more than  $10^{13}$  80 GeV protons.

#### Alternative V

Taking the suggestion from the CERN scheme, Teng<sup>6</sup> recently proposed rebunching of the beam in the Main Ring prior to extraction and transfer to the Energy Doubler. The idea is to first adiabatically debunch the beam and then recapture it at a lower frequency. Thus the number of bunches could be decreased from about 1000 down to about 100 and the number of protons per bunch will increase by a corresponding factor. This beam manipulation seems fast and effective. At the end, bunches would be spaced by 200 nsec and squeezed within 20 nsec.

In this alternative the 80 GeV proton beam will be rebunched at 5.3 MHz. The storage ring is assumed to have a size one tenth that of the Main Ring and the ordinary 53 MHz RF system. The proton beam will be extracted and targeted one bunch at a time; the corresponding bunch of  $\bar{p}$  will then be transferred to occupy one bucket in the storage ring. This will be done sequentially until all the RF buckets are filled and the Main Ring is empty. We assume that this operation can take at most half-second. A crucial aspect of this scheme is clearly a fast injection kicker, since in the storage ring bunches will be spaced by only 20 nsec.

The new, freshly injected pulse will be precooled and stacked as explained above. We assume again a cooling time of two seconds. The Main Ring cycle is now 2.5 sec and  $5 \times 10^7$   $\bar{p}$  will be produced per cycle leading to an accumulation rate of  $2 \times 10^7$   $\bar{p}$ /sec.

Several more alternatives are obviously possible which are given by combining two of the techniques explained above. The main result is shown in Table III.

Table III. Alternative Schemes for Fermilab

Alternative	MR/ED cycle period	$\bar{p}$ /cycle	Accumulation Rate
Basic Scheme	2.8 sec	$4 \times 10^6$	$1.4 \times 10^6 \bar{p}/\text{sec}$
II	28	$5 \times 10^7$	$1.8 \times 10^6$
III	3	$5 \times 10^7$	$1.7 \times 10^7$
IV	46	$5 \times 10^8$	$1.1 \times 10^7$
V	2.5	$5 \times 10^7$	$2 \times 10^7$
IV and III combined	21	$5 \times 10^8$	$2.4 \times 10^7$
IV and V combined	20.5	$5 \times 10^8$	$2.4 \times 10^7$

In conclusion it seems that stochastic cooling at large  $\bar{p}$ -energies could give higher accumulation rate, by at least an order of magnitude if properly combined with a beam manipulation like rebunching or RF stacking.

Note that an accumulation rate of  $2.4 \times 10^7 \bar{p}/\text{sec}$  would correspond to a filling time of about an hour for  $10^{11} \bar{p}$ , required for a  $p\bar{p}$  luminosity of  $10^{30}$ - $10^{31} \text{ cm}^{-2}\text{s}^{-1}$ . Such filling time is comparable to that required to fill the two ISR rings and therefore quite meaningful.

#### Last Moment Comment

In the previous discussion of the alternatives we have been proposing involving stochastic cooling, we have been using the yield for  $\bar{p}$ -production as given in the CERN scheme. Actually because there is a difference in the primary proton energy, and the  $\bar{p}$ -energy is selected to optimize the yield, there should be a factor of about five in  $\bar{p}$ -production yield increase. Thus the accumulation

rates shown in Table III should be multiplied by this factor.<sup>5</sup>

Then the single application of the CERN scheme to Fermilab (Alternative II) already would give  $\sim 10^7$   $\bar{p}$ /s; all the other alternatives would also lead to  $\sim 10^8$   $\bar{p}$ /s. At these rates, the accumulation time is only of a fraction of an hour.

#### References

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